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Research on the Integration of Autonomous Underwater Vehicles and Digital Twin Technology

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Abstract. Autonomous Underwater Vehicles (AUVs) have become critical instruments in exploring and developing resources within the ocean, but they also pose fundamental problems when being used underwater, including the problem of delays in communication, difficulty in monitoring systems, and the problem of not being seen. This is because Digital Twin technology offers an innovative method of solving the real-time state understanding, smart operation and maintenance, and decision-supporting AUVs by developing the dynamic, interactive virtual embodiments of the physical objects. The paper examines the present-day research on the topic of AUVs and Digital Twin integration. One, it provides the basic principles of the AUV systems and Digital Twin technology, the data flow and integrated system architecture. It then outlines the major enabling technologies of realizing this integration in three dimensions high-fidelity modeling, underwater data interaction and transmission and 3D visualization and human-machine interaction. Lastly, the paper examines the key issues that face the integration, which include bottlenecks in the underwater acoustic communication process, the underwater process of dynamic model calibration, and the constraint of AUV onboard processing power and energy consumed. It also includes a perspective of the direction in the future, including the trend towards lightweight edge computing, cloud-edge cooperation, and predictive health. The study has shown that thorough combination of these two technologies can significantly improve the safety, reliability and intelligence of the operations of the AUVs. Submarine autonomous search systems. It is hoped that in the future, it will be applied in deep-sea scientific research, operation and maintenance of underwater infrastructure, military uses, and the underwater Internet of Things.

Keywords: Autonomous Underwater Vehicle (AUV), Digital Twin, High-Fidelity Modeling, Intelligent Operation and Maintenance, 3D Visualization.

1. Introduction

The ocean is home to an incredible number of biological, mineral and energy resources and has immense strategic potential covering more than 70 percent of the Earth. But, the high pressure, dark and low temperature environment, as well as communication challenges of the deep-sea makes it a formidable barrier to direct human exploration. As untethered unmanned underwater vehicles which depend on inherent propulsion and self-directed smarts to perform their tasks, Autonomous

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Underwater Vehicles (AUVs) have become an essential component of missions such as deep-sea surveys, seabed mapping, and pipeline surveillance due to the broad area of operation and great level of autonomy [1].

The submerged condition AUVs face near complete communication cessation of real-time, high-bandwidth information transfer between the underwater, low-bandwidth environment of the AUVs and the surface support platforms (e.g., mother ships) [2]. Operators find it difficult to know accurately and live the location of the AUV, its state of operation (such as battery level, state of equipment, etc.), mission progress, or any unforeseen challenge, as they would with drones or ground robots. Such a position on submergence is catastrophic to the flexibility of the AUV to operate in dynamic active environments and ensure safety in carrying out the mission. Digital Twin technology can be used to solve this critical issue. Digital Twin concept as a basic technology of Industry 4.0 suggests the creation of a complete lifecycle, the dynamically updated digital reflection of a physical object. There is potential, through the combination of Digital Twins with AUVs, to create a synchronized and equivalent of the actual AUV at the surface, which can visualize the underwater AUV in real-time, evaluate its status, foresee potential malfunctions, and make decisions together, which are the main issues of the underwater AUV; it is a non-seeable and uncontrollable. "

This paper aims to systematically review the research progress on the integration of AUVs and Digital Twins [3]. Section 2 of the paper will explain the principles and architecture of the AUV and Digital Twin integration at the systemic level. Section 2 will discuss the basic principles and the structure of this integration. The analysis of the major enabling technologies necessary to facilitate this integration will then be done in depth in Section 3. Section 3 will be a detailed examination of the best technologies needed to make it come true. In line with this, Section 4 will give the main current challenges and future development trends. The key present issues and trends of development will be addressed in Section 4. A final summary is given in section 5.

2. Fundamental principles of AUV and Digital Twin integration

The integration of AUVs and Digital Twins relies on a clear delineation of the physical and virtual entities, coupled with efficient data interaction between them.

2.1. System composition of AUVs

As the physical entity, an AUV typically comprises the following core subsystems: Power system (primarily high-energy-density batteries), propulsion system (motors and propellers), perception system (e.g., multibeam sonar, side-scan sonar, Doppler Velocity Log, Inertial Navigation System, cameras), and navigation and control system (including the main control computer and control algorithm software). Together, these systems enable the AUV to function as a mobile intelligent terminal capable of autonomous navigation and autonomous collection of multimodal environmental and self-state data.

2.2. Core elements of Digital Twins (virtual entity)

Corresponding to the physical entity, the Digital Twin of an AUV is a virtual mapping constructed in the information space. The Digital Twin of an AUV is a comprehensive mapping of its physical entity in the information space, generally encompassing three levels:

(1) Geometric model: precise 3D models reflecting the AUV's external dimensions and internal structure;

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(2) Physical model: models based on physical laws (e.g., fluid dynamics, kinematics) for simulating the AUV's underwater motion, forces, and energy consumption;

(3) Behavioral/Rule-based model: defines the AUV's decision logic, mission planning, and control strategies under specific conditions [3].

Together, these constitute a virtual entity capable of simulating, reflecting, and predicting the state and behavior of the physical AUV.

2.3. System architecture and data flow

The physical and virtual entities are tightly connected through a bidirectional closed-loop system, the operation of which follows a specific data flow. The integration of AUVs and Digital Twins forms a bidirectional interactive closed-loop "physical-virtual" system. Its typical data flow is as follows:

(1) The underwater AUV collects environmental data (depth, temperature, salinity, topographic imagery, etc.) and its own state data (position, attitude, velocity, battery voltage, component temperatures, etc.) in real-time via its onboard sensors.

(2) The AUV sends pre-processed and compressed key data to the surface communication buoys or the mother ship through underwater acoustic communication links through sound waves. This information is then transmitted to the data center either through satellite or radio.

(3) The Digital Twin is analysed by operators or cloud-based intelligent algorithms, which are state-analysed, fault-diagnosed, mission-simulated, or path-replanned. Decision commands (e.g., new waypoints, obstacle avoidance commands) are then relayed to the underwater AUV to be executed through the reverse communication link, and this creates a full cycle of perception-transmission- mapping-decision.

(4) Analytical state analysis, fault diagnosis, mission simulation, or path re-planning operations on the Digital Twin are done with operators or cloud-based intelligent algorithms. The resultant decision instructions (e.g., new waypoints, obstacle avoidance commands) are then relayed to the underwater AUV to be carried out through the reverse communication channel to complete a full perception-transmission-mapping-decision closed loop..

3. Analysis of key technologies for interaction

This is because the successful operation of an AUV Digital Twin system is attributed to breakthroughs in a chain of major enabling technologies. The seamless combination of Digital twins and AUVs greatly improves operation situation awareness, intelligent decision-making, and efficiency of AUVs maintenance by using high-fidelity modelling, 3D visualization, and data-driven strategies.

3.1. High-fidelity modeling technology

Constructing a high-fidelity Digital Twin is fundamental to system effectiveness, primarily including:

(1) Geometric Modeling

The creation of the 3D representation of the AUV and its main components based on CAD, 3D scanning, and technologies [4], which helps to create the accurate 3D model thereof.

(2) Physical Modeling

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Extending the geometric model, the physical model is the basis towards realization of dynamic simulation. The use of Computational Fluid Dynamics (CFD) to model the hydrodynamic properties of the AUV at various velocities and orientations and construct multibody dynamics models to model the velocity response. The models are significant towards attaining the proper simulation of motion and energy consumption forecasting [5].

(3) Data-Driven Modeling

On the basis of historical AUV operational data (e.g., battery discharge curves, sensor errors, control responses in definite sea conditions), learning with the help of machine learning and deep learning algorithms. This assists in creating data-driven surrogate models or digital shadows to augment and modify first-principles-based physical models to increase the flexibility of the model in complicated and non-standard settings.

3.2. Water data interaction and transmission technology

This constitutes the greatest engineering problem of AUV Digital Twin systems.

(1)Underwater Acoustic Communication Technology

It is now the only available method of long-range underwater communication with AUVs. Nonetheless, it is by its very nature a system with very low bandwidth (usually in the range of kbps), a long propagation delay, a high bit error rate, a high power consumption, and a strong dependency on the surrounding environment (multipath effects, noise). These have severe limits on the real time character and the amount of data uplink [6]. (2) Data Compression and Processing

To cope with bandwidth limitations, intelligent data compression and feature extraction must be performed on the AUV side. For example, after performing edge detection or target recognition on acoustic images or video data, only key feature information or anomalous segments are uploaded instead of the raw, massive data.

(3) Hybrid Communication Modes

Adopting a layered communication strategy. While submerged, the AUV uses acoustic communication to transmit low-bandwidth, high-priority commands and status data. When the AUV periodically surfaces or operates in shallow water, it switches to radio, 4G/5G, or even satellite communication for batch uploads of large data volumes (e.g., HD video, detailed survey data) and model updates [7].

3.3. Visualization and human-machine interaction technology

3D visualization and human-machine interaction technologies are primarily manifested in the following two aspects:

(1) Real-Time 3D Rendering

Utilizing game engines like Unity3D [8], Unreal Engine, or professional visualization development frameworks to build an immersive virtual ocean environment, including dynamic sea surface, seabed topography, water effects, and marine life. The real-time updated AUV Digital Twin and its sensor data (e.g., sonar scan sectors) are fused and rendered, providing operators with a global, intuitive situational awareness [9].

(2)Augmented Reality (AR)/Virtual Reality (VR)

Operators can wear VR headsets to "enter" the virtual ocean environment, observing the AUV and its surroundings from a first- or third-person perspective for immersive mission monitoring and equipment inspection. AR technology can overlay the AUV's twin data, predicted flight paths, and other information onto the real view of the mother ship's control room or nautical charts [10].

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4. Current challenges and future trends

4.1. Main current challenges

(1) Communication Bottleneck

The poor bandwidth and latency rates of underwater acoustic communication lead to significant time-delay asynchrony between Digital Twin state updates and the physical object, which makes real-time fine-grained.

(2) Fidelity Maintenance and Dynamic Model Calibration.

Marine environment is diverse and unpredictable, with unknown currents, biological disruptions, etc. The already developed models find it difficult to adapt to the real time dynamic environment. The twin system needs online learning and adaptive capabilities of calibration which places heavy burdens on algorithms and computing power.

(3) AUV Onboard Processing Power and Energy Constraint.

The complicated modelling, data compression and calculation of edge intelligences require high processing power which is in direct opposition to the small onboard energy and heat dissipation capacity of the AUV. One of the important factors to consider when designing a system is its ability to balance between local and cloud intelligence.

4.2. Future development directions

The digital twin systems of the future AUV are likely to have three aspects of evolution:

(1) Lightweight Edge Intelligence

Lightweight Edge Intelligence is a method of operations that turns the application over to the present system provider. Lightweight AI models that are optimized by methods such as pruning, quantization, and knowledge distillation will be added to future AUVs. This allows them to have real-time environmental perception, local path planning and initial fault diagnosis on the edge as opposed to continuous high-bandwidth communications and provide autonomous responses much faster [11].

(2) Integration of Digital Twins with Cloud Platforms and Edge Computing

Recent progress in digital twins and integration with cloud computing and edge computing is expected to accelerate and simplify deploying digital twins for remote diagnostics and predictive maintenance management. Digital Twins + Cloud Platforms + Edge computing Digital twins and cloud computing along with edge computing may help increase the speed and ease of deploying digital twins in remote diagnostics and building a jointly distributed cloud-edge- device architecture. The cloud systems unite information of multiple AUVs and form a macroscopic Digital Twin of local or even the global oceans - a single integrated map. Edge computing Edge computing nodes (e.g., mother ships, surface stations) process regional real-time data, and make joint decisions, which create a layered intelligence structure.

(3) Intelligent Prediction and Health Management:

Digital Twins will no longer be a description of the current state, but a forecast of the future. With the use of constant monitoring and the analysis of operational statistics (vibration, current, temperature, etc.) of AUV parts with the help of the machine learning, the possibility to predict the remaining life of the important components (e.g., thrusters, batteries) and attain early warning of failures appears. This transforms the paradigm of maintenance into a predictive maintenance paradigm whereby the maintenance is no longer done on a scheduled basis but rather predictively thereby increasing the reliability of missions and the utilization of equipment massively [12].

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5. Conclusion

The paper is a systematic review of the studies conducted regarding the Autonomous Underwater Vehicles and Digital Twin technology integration. As explained in the study, such interaction between technologies by building a two-way interactive physical-virtual closed-loop system provides a new technical solution to the state of the black box of AUVs in the course of underwater activities. The essence is that it enables the real-time visibility, understanding and control of AUVs by the use of perception-transmission- mapping-decision process. The current state of progress on this area is limited by the inherent bottlenecks of underwater acoustic communication, the challenge of dynamically calibrating models of high fidelity, and the resource constraints of the AUV platforms themselves. Nevertheless, as artificial intelligence algorithms continue, advances in underwater communication systems and strengthens in the edge computing capabilities, the digital twins and AUVs integration is set to take a more intelligent, collaborative, and autonomous turn, eventually becoming one of the technological pillars of the future intelligent, networked marine observation and operating systems.

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